THE INFLUENCE OF TECTONIC BOUNDARIES ON GEOMAGNETIC VARIATIONS IN THE SCOTIA SEA

D. BEAMISH
Institute of Geological Sciences, Murchison House, West Mains Road, Edinburgh, EH9 3LA

and

R. A. HAMILTON
British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET

ABSTRACT. Geomagnetic variation fields recorded at a particular location can be analysed to provide information on the distribution of induced currents within the Earth. An analysis of the variation fields on South Georgia, in the Scotia Sea, has revealed some unusual features in the geomagnetic response characterizing the distribution of internal currents. Both vertical and horizontal components of the variation fields appear anomalous with respect to the behaviour expected for a deep ocean island such as South Georgia. It is suggested that the anomalous variations can be accounted for by lithospheric conductivity contrasts between the older South American and much younger Scotia plates.

A Rubidium Vapour Magnetometer was installed at the British Antarctic Survey's research station at King Edward Point, South Georgia (54.26°S, 36.50°W. geographic; −44.04°, 25.89°, centred geomagnetic; declination 8°W) in February 1975 for the study of geomagnetic pulsations. The instrument is similar to that at Halley (Hamilton, 1982) and to those in the network of magnetometers run by the Geomagnetism Unit of the Institute of Geological Sciences. A preliminary analysis of early records on paper charts by Hamilton (1979) showed that magnetic variations of periods 16–60 min are strongly polarized in a north-north-easterly direction. This was attributed to induced currents in the ocean or in the mantle below South Georgia. Digital recording on cassette, sampling horizontal and vertical components at 2.5-s intervals, was introduced in July 1976; this enabled a deeper study to be made using computer analysis methods, resulting in this paper, which extends the analysis of the horizontal components and includes an analysis of the vertical field.

THE ANOMALOUS HORIZONTAL FIELD

For this study 20 days were selected in which there was no break in record (changing cassette causes a break) and on which the magnetic activity was moderate. The data on these days were analysed using complex demodulation (Banks, 1975) which is a convenient spectral technique for the determination of the polarization of characteristics of both harmonic and band-averaged data. Data lengths of 3 h were used to enable a universal time (UT) dependence to be studied. Each complete day provided eight 3-h data files. The procedure obtains the azimuth, θ, of the major axis of the horizontal field ellipse from complex demodulation over 6 period bands obtained from each 3-h data file. The period bands (B1–B6) together with the number of polarization states sampled in each band are given in Table I.

The results showing the normalized distribution of azimuths in 10° sectors as a function of UT and period band are shown in Fig. 1. The results confirm the findings of the preliminary analysis which was carried out for periods approximating those of bands B1 and B2. A highly skewed distribution is apparent throughout the period

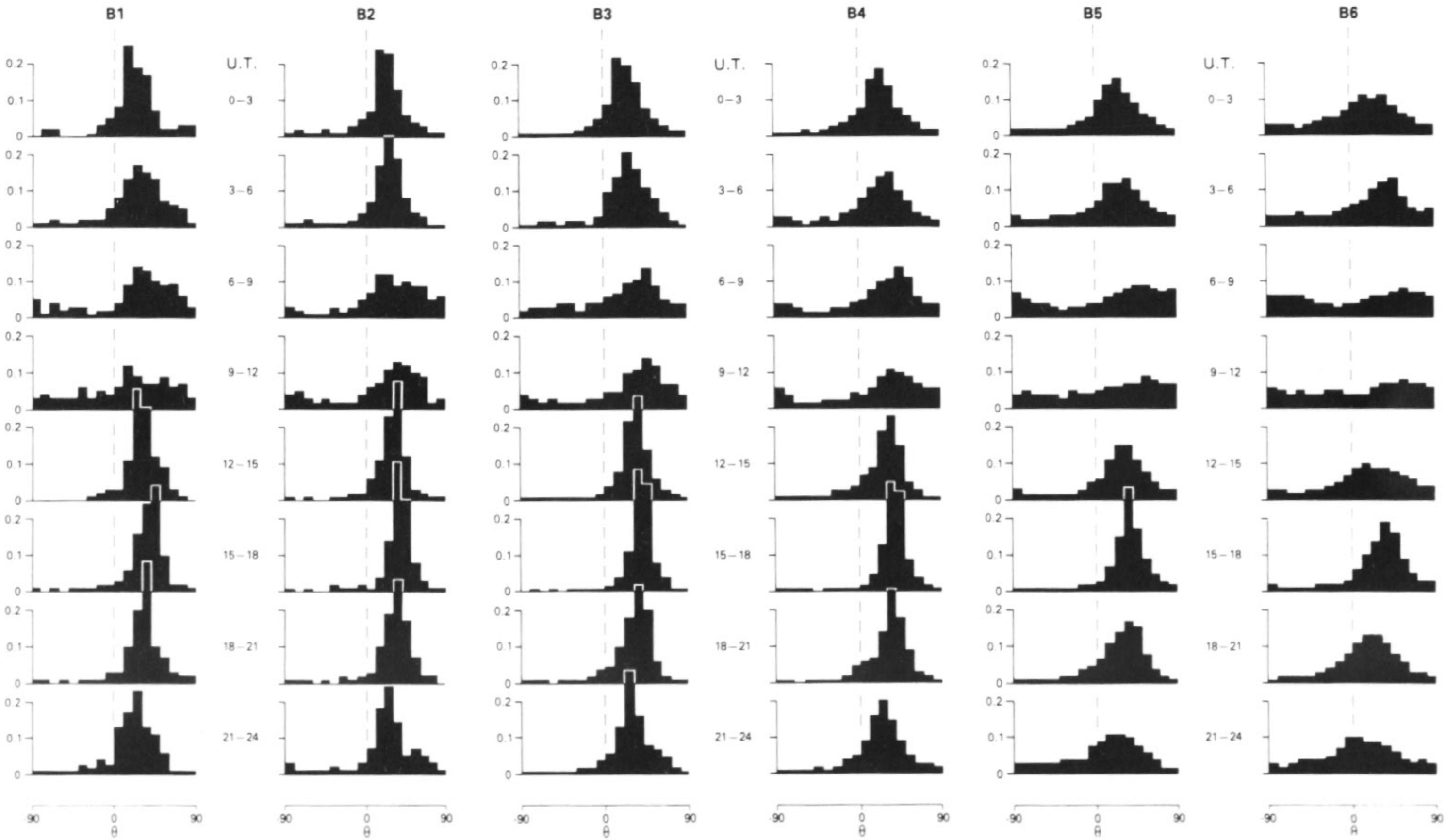

Fig. 1. Normalized distribution of the azimuth (θ) of the major axis of the horizontal field polarization ellipse as a function of UT and period band (B1–B6). The azimuth is defined positive clockwise from geomagnetic north.

Table I. Period bands and number of polarization states sampled in each band (NP) for the analysis of the observed horizontal field.

Band	*Period range (s)*	*NP*
B1	2 000–1 000	16
B2	1 000–500	32
B3	500–250	64
B4	250–125	128
B5	125–62.5	256
B6	62.5–31.25	256

range. The major axis is largely confined to the geomagnetic azimuth range $10° < \theta < 50°$. The only modification introduced as a UT dependence is a tendency towards a more uniform distribution during 0600–1200 UT (0830–1430 LT). The likely cause of such a feature is a local time minimum in the source field amplitude. It is apparent from Fig. 1 that the distributions for the longest period bands exhibit the most skewed form.

The above analysis was then carried out on similar records for two stations in the northern hemisphere at roughly the same latitude (54°), but some 10° higher in geomagnetic latitude. One of them, VA, situated on the west coast of Ireland is a typical coastal site (i.e. influenced by the European continental shelf) while the other, YO, is a typical mainland site. The analysis showed that, for these two stations, there is no significant difference in the distributions of azimuths of the major axes of the horizontal field ellipse, either as a function of period, or UT. It is true that they both showed a skewed form between 1200 and 1800 UT but there is no suggestion that the azimuths are highly constrained independently of period and UT as in the case at South Georgia.

The Anomalous Vertical Field

The measured vertical field contains a contribution caused by the horizontal earth currents induced by the normal (i.e. source) variations in the horizontal field. The anomalous induced vertical field is related to the inducing field by

$$Z_a = A \cdot H_n + B \cdot D_n \tag{1}$$

where all quantities are complex and period dependent. With only single station data available we assume that for the vertical field the normal component is small and does not contribute significantly to Z_a, and also that, for the horizontal field it is, conversely, the anomalous components that are small. Thus we rewrite

$$Z = A \cdot H + B \cdot D + \epsilon \tag{2}$$

where Z, H, and D are the measured values, and ϵ represents an uncorrelated residual. We determine A and B by minimizing ϵ, it being assumed also that in the long run and over all the hours of the day the three magnetic components of the source field are not correlated.

The equations

$$G_R = (A_R^2 + B_R^2)^{1/2}$$

$$G_I = (A_I^2 + B_I^2)^{1/2}$$

$$\theta_R = \tan^{-1}(-B_R/A_R)$$

$$\theta_I = \tan^{-1}(-B_I/A_I)$$

define an induction arrow with magnitude G and azimuth θ which is normal to the strike of a local conductive boundary, azimuth being measured from geomagnetic north. The subscripts R and I refer to real (0° phase) and imaginary (90° phase) parts of the complex pair (A, B). These quantities have been determined in a period range 10–10^4s for 18 period bands distributed evenly on a logarithmic period scale and covering the range 20–7200s; they are plotted in Fig. 2.

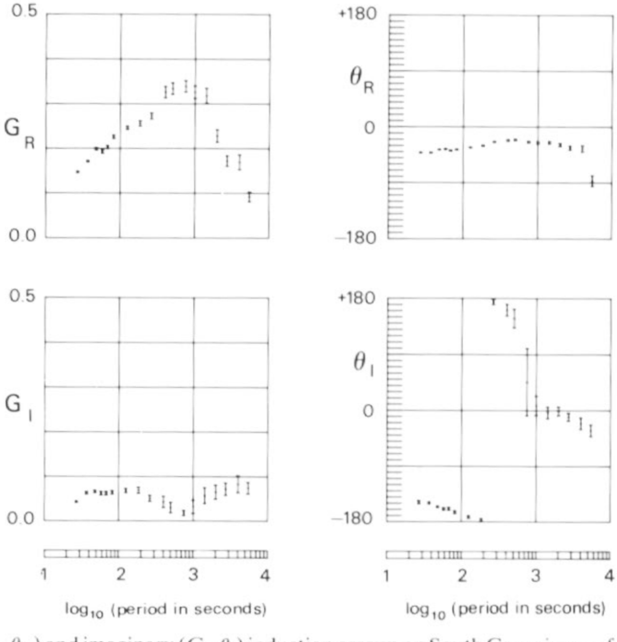

Fig. 2. Real (G_R, θ_R) and imaginary (G_I, θ_I) induction arrows on South Georgia, as a function of period.

Throughout the period range the magnitude of the real arrow G_R is consistently larger than the imaginary arrow G_I. The real response is strongly period dependent reaching a maximum of 0.33 at 800s. The azimuth θ_R of the real arrow is constant up to a period of 5000s while θ_I shows a smooth transition from a northerly direction for $T > 1000$s to a southerly direction for $T < 200$s.

The corresponding results obtained at Halley (75°S, 26°W) are shown in Fig. 3. It should be noted that Halley station lies on the Brunt Ice Shelf some distance from the continental land mass of Antarctica (Thomas, 1973) and as such must be viewed as seaward of the true ocean-edge. The azimuthal response as defined by θ_R lies in the south-east quadrant (with respect to geomagnetic north) and is therefore compatible with the station's position above the shelf of the Weddell Sea. For the purposes of our present discussion with regard to the observed vertical field response on South

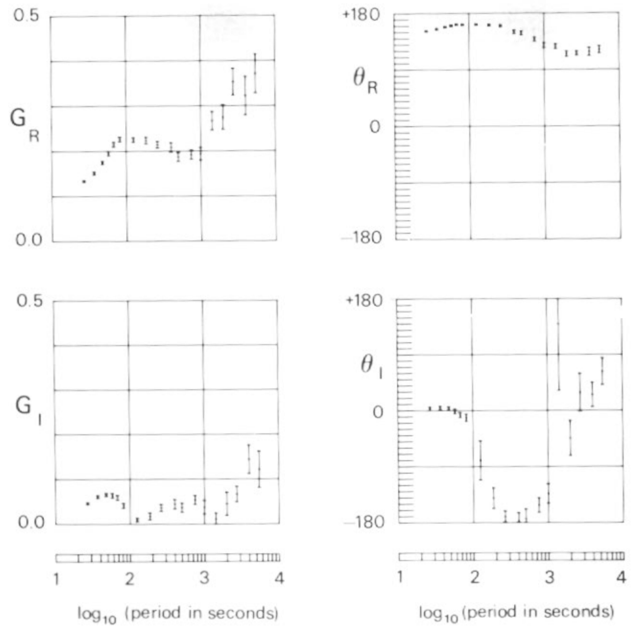

Fig. 3. Real (G_R, θ_R) and imaginary (G_I, θ_I) induction arrows at Halley, as a function of period.

Georgia we wish to point out the differences observed in Figs. 2 and 3 in the magnitude of the real arrow G_R at long periods (>1000 s). We note that whereas at Halley G_R increases with increasing period, on South Georgia the opposite effect occurs.

The Geographic Location

South Georgia is a mountainous island about 150 km long running approximately ESE–WNW and rising to heights of about 3 000 m. The station at King Edward Point is on the northern coast where the width of the island is about 30 km. The island is situated symmetrically on the continental shelf which extends about 80 km from either coast and where the sea bottom plunges abruptly from depths around 300 m to over 3 000 m (Fig. 4).

The Geomagnetic Coast Effect (GCE) is observed on the landward side of continental margins: it is characterized by a large increase in the vertical field as the continental edge is approached while there is a smaller increase in the component of the horizontal field normal to the continental edge. These anomalous fields result from the difference in conductivity of ocean and continent.

Several workers have developed models for the GCE. Recently Raval and others (1981) have developed an ocean-crust model consisting of a thin-sheet, conducting half plane representing the ocean, and deduced values of G_R, G_I, θ_R and θ_I in terms of the distance of the station from the ocean edge expressed in skin depths in the underlying half-space. The skin depth, d, is period dependent and is given approximately by

$$d = 0.50\,(T/\sigma)^{1/2}\,\text{km}$$

where T is the period of the incident field in seconds, and σ is the conductivity in $S\,m^{-1}$. For South Georgia, the distance of the ocean edge from the station is taken as 80 km and taking σ as $5 \times 10^{-3}\,S\,m^{-1}$, the normalized distance is given by

$$n = 80/d$$

$$n = 11.3\,T^{-1/2} \text{ skin depths}$$

The magnitudes of the real (G_R) and the imaginary (G_I) induction arrows obtained by Raval and others are plotted in Fig. 5, in which the abscissa is given in skin depths; both arrows increase with increasing period, with G_R pointing towards the ocean and G_I inland. In Fig. 5 are also plotted the observed values of G_R. It can be seen that for short periods the observed values, though larger than the theoretical values, show a

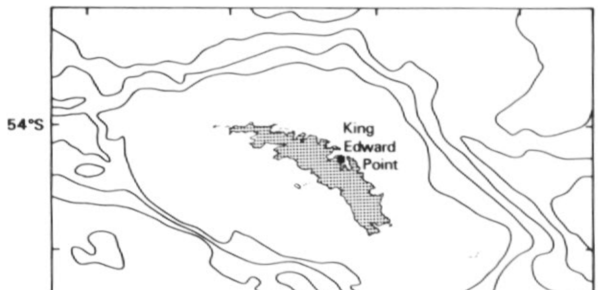

Fig. 4. Location of BAS station at King Edward Point on South Georgia and bathymetry of the continental shelf at an interval of 1 km.

somewhat similar increase with increasing period, but for periods greater than 800 s there is complete departure, G_R decreasing rapidly instead of increasing. Different normalizing parameters would not alter the main features of the comparison. Nor does the observed value of θ_R agree with the model value: Fig. 2 shows θ_R to be around $-40°$, ($-30°$ geographic), i.e. roughly parallel to the ocean-edge, and nearly at right angles to the theoretical values. The values of G_I and θ_I show no better agreement with the model (see Fig. 2). The values of G_R, θ_R at Halley (Fig. 3) at long periods show no such anomaly, being approximately compatible with the ocean-crust model considered by Raval and others (1981).

The anomalous value of θ_R at South Georgia may be explained by recalling that in going from equation (1) and (2) we assumed that the anomalous horizontal components are small. However, the strong polarization of the horizontal components show that this is not so. It has been shown by Beamish (1977) that when substantial anomalous horizontal components are present, the induction arrows are rotated in a direction determined by a ratio of the anomalous components H_a/D_a; in this case the induction arrow tends to a more E–W orientation, though the apparent rotation at South Georgia appears excessive. This, however, does not explain the very anomalous behaviour of G_R at longer periods, and it appears that the induction effects at South Georgia cannot be explained by the ocean-edge effect.

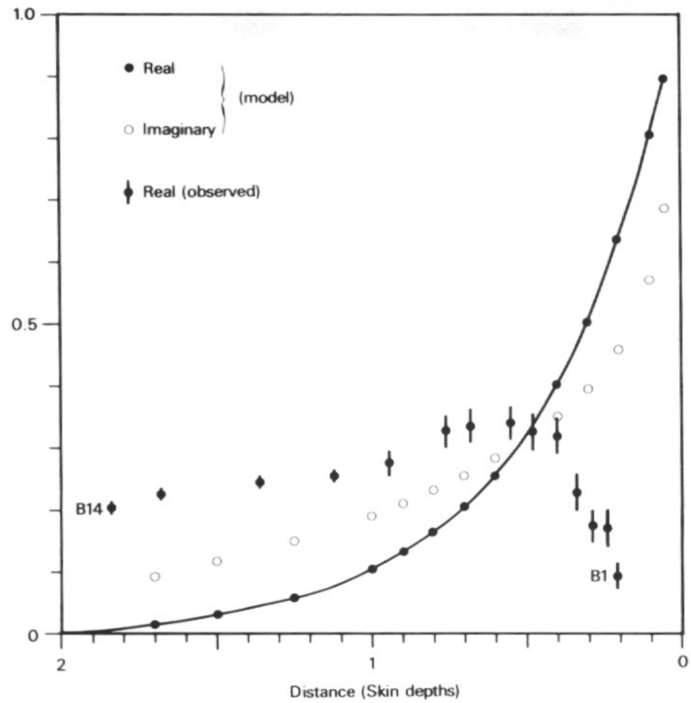

Fig. 5. Magnitude of the real induction arrow observed on South Georgia compared with the magnitudes of the real and imaginary induction arrows obtained from the thin-sheet, ocean-edge effect model of Raval and others (1981). Distance is normalized in skin-depths in the underlying medium from the ocean edge.

Tectonic Relations

Sea-floor spreading is taking place 400 km west of the South Sandwich Trench (Barker, 1972; Barker and Hill, 1981). This constructive plate margin separates the Sandwich plate, SDP, to the east from the Scotia plate STP to the west (see Fig. 6). the latter is bounded to the south by the Antarctic plate ANT and to the north by the South Atlantic plate SAM. South Georgia is a detached block of continental crust on the northern margin of the Scotia plate.

Geophysical surveys of the South Georgia continental shelf have been carried out by Simpson and Griffiths (1982). A plate boundary traverses the northern boundary of the South Georgia block. Relative motions are uncertain, but in the region of South Georgia motion is thought to be a sinistral strike-slip with a convergent component of old ocean floor underthrusting the NW margin of the block (Barker, personal communication, 1980). The South Georgia block, therefore, may be regarded as being transitional between old (~100 Ma) and young (10–20 Ma) oceanic lithosphere. According to Filloux (1980) and Oldenberg (1981) there is a correspondence between the age of oceanic lithosphere and the depth to a conductive zone of partial melt, in which case the South Georgia continental block is a region of strong lateral conductivity gradients at upper mantle depths. Thus the anomalous fields on South Georgia may be due to these deep lateral conductivity gradients. The vertical resolution of geoelectric structure provided by single station geomagnetic data is small: magnetotelluric recording equipment has recently been

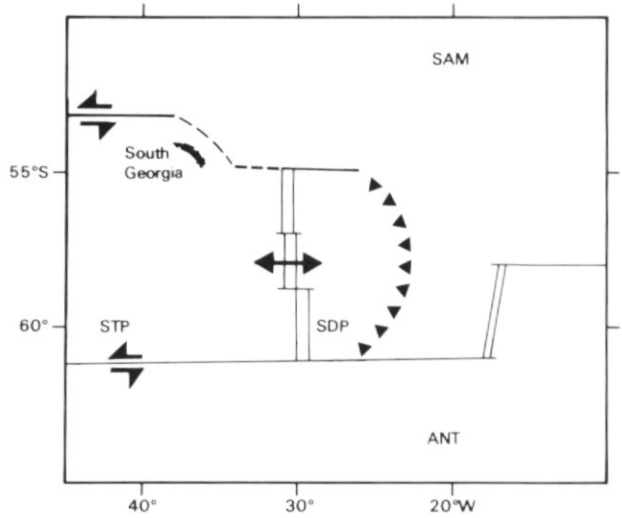

Fig. 6. Plate boundaries and present motions in the region of the Scotia Sea, redrawn from Baker and Hill (1981). SAM: South America Plate, ANT: Antarctic Plate, STP: Scotia Plate, SDP: Sandwich Plate. The serrated arc is a subduction zone with teeth on the overthrust plate.

installed on South Georgia to enable a more complete analysis of the geoelectric structure to be undertaken.

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